COMPLIMENTARY COPY
Please Credit Ontario Hydro Research If
Reproduced in Whole or in Part

ontario hydro
research division

To: Mr. J.L. Phillips
Design & Development - Trans
H09D09

Atmospheric Corrosion of Transmission Line Conductors - Literature Review

A. Kalvins
Scientist - Environmental Controls
Environmental Science Section
Chemical Research Department

ABSTRACT

Transmission line conductors consist of strands of aluminum wound around a core of galvanized steel. Many atmospheric pollutants such as SO_2, NO_x and Cl^- in the presence of the proper meteorological conditions, high relative humidity, precipitation, fog or dew, etc., will cause significant rates of corrosion of aluminum and zinc (galvanized steel). This report presents a brief review of the atmospheric pollutants, their reactions and the meteorological conditions responsible for the corrosion of aluminum and galvanized steel in the atmosphere. An attempt is made to relate this information to transmission line conductors, and hence identify pollutants and meteorological conditions which might affect the life of the conductors.

1.0 INTRODUCTION

Transmission line conductors consist of strands of aluminum wound around a core of galvanized steel. There are several conductor constructions in use. One typical construction contains a centre core of 7 galvanized steel wires and 26 aluminum wires, in two layers, wound around the steel core.

job	file	date	report no.
35-104-431	825.154	November 2, 1989	89-252-K

LEGAL NOTICE

This report was prepared by Ontario Hydro and, while effort has been made to assure the accuracy and applicability of the material contained herein, neither Ontario Hydro nor any person acting on its behalf:

(a) makes any warranty, express or implied, with respect to the use of any information, apparatus, method or process disclosed in this report or that such use may not infringe privately owned rights; or

(b) assumes any liabilities with respect to the use of, or for damages resulting from the use of, any information, apparatus, method or process disclosed in this report.

Many atmospheric pollutants such as SO_2, NO_x and Cl^- in the presence of the proper meteorological conditions, high relative humidity, precipitation, fog or dew, etc., will cause significant rates of corrosion of aluminum and zinc (galvanized steel). The rates of corrosion vary with season, temperature, type of atmospheric pollution, length of time the object remains wet, the intermittent removal of water-soluble salts by rainfall, time of initial exposure and the presence of moisture in the corrosion product film/1/.

Most of the corrosion data collected for galvanized steel and aluminum, in fact all materials, are from coupon samples, eg, small flat squares, exposed to the atmosphere on racks mounted at 30 to 45 degrees to the horizontal and facing south/2/. Transmission line conductors are however very different physically and chemically to such coupons. The crevices formed by winding of the aluminum wires about the galvanized steel core wires trap considerable amounts of particulate matter and moisture. This configuration results in significant differences in the drying times of the wires relative to flat coupons. The conductors are strung between transmission towers hence the water and pollutants trapped between the wires will tend to flow to the lowest point in the strand. One layer of the aluminum wires is in constant contact with the galvanized steel wires. As the protective coatings on the two materials break down this contact may result in galvanic corrosion. The temperature of the lines is also significant. The conductors are generally at close to ambient temperature but for short periods of time the temperature may vary from 49 to 150°C. A factor of unknown importance is the effect of current in the wires on the attracting or repelling of surrounding dusts and aerosols.

This report presents a brief review of the atmospheric pollutants, their reactions and the meteorological conditions responsible for the corrosion of aluminum and galvanized steel in the atmosphere. An attempt is made to relate this information to transmission line conductors, and hence identify pollutants and meteorological conditions which might affect the life of the conductors.

2.0 ATMOSPHERIC POLLUTANTS

Aluminum and zinc are known to be susceptible to degradation in varying degrees by SO_2, NO_x, HCl/Cl^-, H_2O_2, $(NH_4)_2SO_4$ and alkali salts/3/. The effect of alkali salts are not however well characterized. Particles most often found to be corrosive are characterized by the presence of soluble chloride and/or species of sulfur (S), manganese (Mn) and iron (Fe). Specifically these include salt/sand particles, incinerator particles, smelter ash smut and fly ash from coal/4/. The effect of formaldehyde (HCHO) or formic acid (HCOOH) is not well known.

Sulfur dioxide, SO_2, is usually considered to be the cause of atmospheric corrosion. It is however the sulfate ion, SO_4^{2-}, which takes part in the corrosion mechanisms. Oxidation of SO_2 is therefore a significant step in the corrosion mechanism. The reactions involved in

the oxidation of SO_2 to SO_4^{2-} in the atmosphere, liquid phase, are given in equations (1) to (5).

$$SO_{2(g)} \longrightarrow SO_{2(aq)} + H_2O \longrightarrow H^+ + HSO_3^- \quad (1)$$

$$HSO_3^- + H_2O_2 \longrightarrow HSO_4^{2-} + H_2O \quad (2)$$

$$HSO_3^- + O_3 \longrightarrow HSO_4^- + O_2 \quad (3)$$

$$HSO_3^- + [O] \longrightarrow HSO_4^- \text{ (Fe, Mn)} \quad (4)$$

$$HSO_4^- \longrightarrow H^+ + SO_4^{2-} \quad (5)$$

The reaction shown in equation (4) involves catalytic oxidation by iron or manganese ions. This oxidation reaction can be significant in heterogeneous systems involving particulate pollutants/4/.

Dissolution of SO_2 in the layer of moisture on a surface is sensitive to pH. Buffering of the moisture layer by corrosion products is essential for SO_2 deposition to continue/5/.

Ammonium salts can be very effective in initiating corrosion, probably because they produce solutions of low surface tension which are much more acid than the corresponding sodium salts/6/. Microscopic crystals of solid ammonium sulfate, $(NH_4)_2SO_4$, may form reservoirs capable of maintaining a local SO_4^{2-} concentration higher than that produced by a film of very dilute sulfurous or sulfuric acid. $(NH_4)_2SO_4$ has been found to promote rusting even in the absence of SO_2/7/.

HCl is generally formed in the combustion process from chloride found naturally in coal, however the contribution for most North American coals is small relative to British coals. HCl is also formed from the incineration of certain plastics, this may be a more important source for urban areas/2/. Other sources of chloride ions include the degradation of methyl chloride or freons/8/ and road salt. In marine environments chlorine enters the aqueous surface layer through the deposition of sea salt. Chlorides are believed to enhance the effects of SO_2 or sulfates, this may be due to an increase in the time of wetness due to deliquescence.

Formic acid is abundant in rain and snow, probably present in clouds and fog and possibly present in ice/3/. Once present in the surface film, formaldehyde is readily transformed into an organic acid (formic acid) by transition metal ions, hydroxyl radicals (OH), etc. (8)

3.0 METEOROLOGICAL CONDITIONS

Atmospheric corrosion is electrochemical in nature and moisture must be present for it to occur/1/. Two terms often encountered during the discussion of atmospheric corrosion, which relate the water content of a surface to corrosion, are "time of wetness" and "critical relative humidity". The time of wetness is a complex function of relative humidity, surface contaminants and surface roughness. Pollutants can affect the time of wetness by introducing hygroscopic corrosion products to the metal surface/9/. Critical relative humidity refers to the

relative humidity at which significant corrosion is observed. The presence of pollutants may lower the critical humidity/1/. To illustrate, saturated solutions of certain chlorides are in equilibrium with air at very low humidity values, 12% for LiCl, 31% for $CaCl_2$, 33% for $MgCl_2$ and 40% for $AlCl_3$/10,11/. In contrast to the behaviour of these chlorides, in the presence of sodium borate, benzoate or carbonate there is practically no attack even when the relative humidity approaches 90%/7/. At humidities of <40% comparatively large clusters of water are present on oxyhydride surfaces/1/. In general, the corrosion rate of metals is a continually varying function of relative humidity. Very significant increases in rate are observed at higher relative humidities.

The weather conditions during the initial exposure of the metal surface to the atmosphere are important to the type of protective coating which the metal may develop and may affect its performance months later/1/.

4.0 CORROSION MECHANISMS

4.1 Aluminum

Pure aluminum and its dilute alloys are generally very resistant to atmospheric corrosion/6/. When aluminum is exposed to the atmosphere the initial surface reactions result in the formation of a thin film of aluminum oxide. Serious destruction of the metal with the formation of soluble corrosion products comes later. The rates of corrosion for outdoor atmospheric exposure of aluminum in different environments are <0.1 $\mu m\ year^{-1}$ in a rural setting, approximately 1 $\mu m\ year^{-1}$ in urban areas and 0.4 to 0.6 $\mu m\ year^{-1}$ in a marine environment/12/. These rates are considerably lower than those for carbon steel, zinc or copper. Foley et al/12/ have described the corrosion of aluminum as a four-stage process: i) adsorption of the reactive anion on the oxide-covered aluminum, ii) chemical reaction of the adsorbed anion with the aluminum ion in the aluminum oxide lattice or the precipitated aluminum hydroxide, iii) thinning of the oxide film by dissolution and iv) direct attack of the exposed metal by the anion.

γ-Alumina (aluminum (III) oxide) is the first component formed upon exposure of aluminum to the atmosphere. The initial depth of the layer is 2-3 nm. After a few months of exposure in air, the oxide becomes covered by a thin layer of boehmite (γ-AlOOH). The boehmite layer is subsequently covered by bayerite ($Al(OH)_3$ or $Al_2O_3 \cdot 3H_2O$). Some of the reactions involved in the formation of these oxides are listed below, equations 6-9.

$$Al^0 \longrightarrow Al^{3+} + 3e^- \qquad (6)$$

$$Al^0 + H_2O \longrightarrow Al(OH)^{2+} + H^+ + 3e^- \qquad (7)$$

$$Al^0 + 2H_2O \longrightarrow Al(OH)_2^+ + 2H^+ + 3e^- \qquad (8)$$

$$Al^0 + 3H_2O \longrightarrow Al(OH)_3 + 3H^+ + 3e^- \qquad (9)$$

Reaction (6) is important at pH less than 6. Above pH 7 reaction (9) predominates resulting in the formation of the solid corrosion products AlO(OH) or Al_2O_3. Initially it might seem

that in a neutral liquid film repair would prevail and corrosion would be avoided indefinitely, but the reactions automatically generate H^+ and as a result soon involve destructive corrosion/7/. The hydrated versions of these species, akdalaite ($Al_2O_3 \cdot 1/4H_2O$) and tucanite ($Al(OH)_3 \cdot 1/2H_2O$), have also been observed.

Studies of the aluminum-water system suggest that bayerite is stable over a wide range of acidities. Complete dissolution of the oxide occurs at about pH 2.4 but some dissolution may begin at pH 4. This can have a serious impact on the stability of the layer since most rains and almost all fogs have pH values at this or lower levels. Very low levels of pH are observed in evaporating solutions of deposited electrolytes and in the liquids found in the surface pits on aluminum. In the case of dew, the typical solution is too basic to be expected to dissolve the surface oxide.

The degradation reactions of aluminum in an aqueous environment involve only deposition, dissolution and ion association. There is no oxidation-reduction chemistry of the aluminum ions since only the 3+ valence state is available to aluminum.

Destructive corrosion of aluminum occurs principally at mechanical flaws or grain boundaries. The corrosion manifests itself as deep pits rather than as uniform surface deterioration. Figure 1 summarizes some of the chemical reactions involved in the atmospheric corrosion of aluminum. Pitting is particularly characteristic of chloride ion attack, but may also be seen in carboxylic acid corrosion of aluminum. Corrosion attack extends in a random direction from the pit, but the two tracks do not cross. If they approach, they turn aside or cease to advance. These tracks, filiform corrosion, are generally a surface phenomenon, the maximum depth being approximately 0.005 mm. Filiform corrosion is especially noticeable on an alloy containing approximately 3% magnesium/13/. It occurs at places exposed to the air but not washed by rain. Some have attributed this type of corrosion to dust particles containing chlorides, eg, $MgCl_2$, and due to the presence of MgO which enters the cavities present on an extruded surface/13/. Even at pH values as low as 2, the degradation of the surface layer is still of the pitting type, with some oxide film remaining.

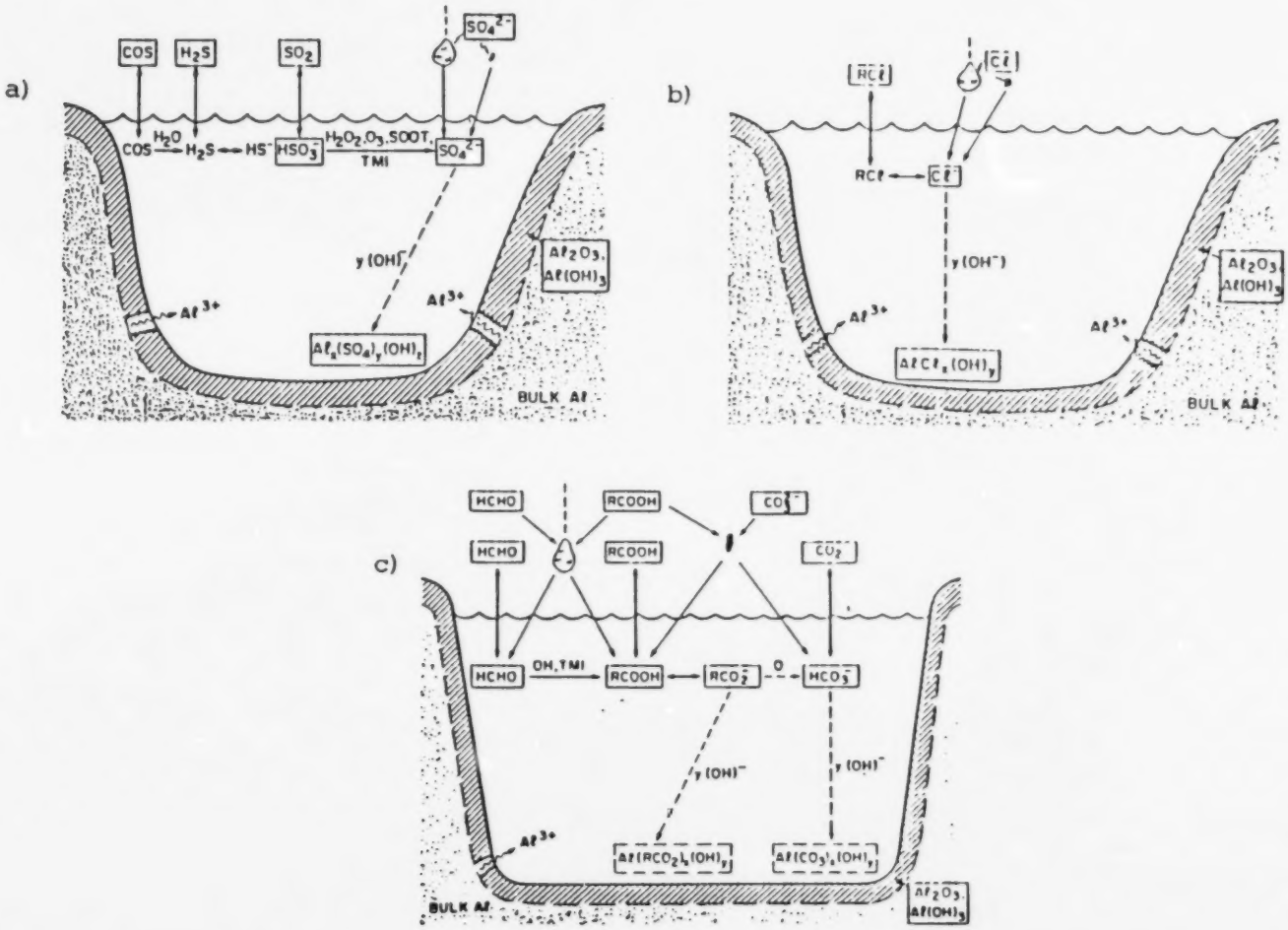
Aluminum takes up less SO_2 than most other metals. Substances such as dust may however act as intermediaries. Aluminum sulfates are among the principal constituents of the degraded surfaces. Amorphous aluminum sulfate hydrate is the most abundant corrosion product on aluminum exposed to marine and industrial atmospheres. The compound has a long lifetime at atmospheric temperatures and pressures, and is formed in the presence of H_2SO_4 at quite acidic pH conditions. Aluminite, a crystalline aluminum hydroxysulfate has also been observed. Equation (10) gives a general reaction to describe the formation of aluminum sulfates/12/.

$$x(Al^{3+}) + y(SO_4^{2-}) + 2(OH^-) \longrightarrow Al_x(SO_4)_y(OH)_z \qquad (10)$$

The stoichiometry of the resulting product is variable, partly as a function of the amount of water available. Generally the Al:S ratio is of the order of 2, $z >> x \approx 2y$/12/.

In areas protected from rain a white floury product accumulates on the surface. This product has been found to contain sulfate, while the condensed moisture contains sulfuric acid.

Figure 1. A schematic representation of the processes involved in the atmospheric corrosion of aluminum. The sulfur chemistry is shown in Figure 1a and similarly the reactions of chlorine containing species in 1b, carbonate and organic compounds in 1c. The atmosphere is at the top of the diagrams, a surface water layer is in the centre, and the corroding metal is at the bottom. The diagram pictures a depression in the metal surface, although deposited hydroscopic particles, heavy dew, or rain could produce similar conditions anywhere on the surface. The wavy lines indicate aluminum ions diffusing into the aqueous solution from the bulk solid. Species whose presence has been confirmed by field measurements are enclosed in a rectangular box; the presence of other species has not been confirmed. Reaction processes confirmed by laboratory studies are indicated by solid arrows, those which are uncertain are shown as dotted arrows. Rain is indicated by the atmospheric water drop and airborne particles by the irregular small atmospheric object/12/.



A significant cause of the degradation of the aluminum surface upon exposure to the atmosphere is the chloride ion. The solubility of the resulting chloride containing products prevents large buildups of chloride surface species, but some chloride is incorporated into the corrosion layer. Chlorine enters the aqueous surface layer through the incorporation of gaseous HCl or an organic gas containing sea salt, background aerosol particles or hydroxy-chlorides. Laboratory studies suggest that the presence of sulfate ion in the chloride solutions enhances the rate of pitting.

Aluminum or aluminum hydroxides have not been found to react with CO_2. Although there is an abundant supply of bicarbonate ions in the aqueous layers exposed to the atmosphere, aluminum carbonate compounds have not been detected on exposed aluminum surfaces.

The effect of organic acids on the corrosion of aluminum is not clear. In the case of acetic acid, thin layers of the acid appear to inhibit corrosion, possibly because of the relatively strong bonding between the carboxylic acid molecule and the hydrated aluminum surface. In the case of formic acid the rate of attack increases at high acidities, therefore if there is a reaction it probably will be present only on acid surfaces/12/.

Nitrates are common constituents of the atmosphere. They are absorbed onto aluminum oxide surfaces and would be expected to participate in the degradation of aluminum. Laboratory studies using very high concentrations of NO_2 suggest acceleration of aluminum corrosion in humid air, but the effect was smaller than that produced by SO_2/12/. Aluminum nitrates have not been detected on aluminum surfaces exposed outdoors. It may be however that the solubility of these species results in their loss in precipitation runoff, etc.

H_2O_2 has not been found to play a role in the atmospheric corrosion of aluminum. In fact aluminum is the metal called most resistant to hydrogen peroxide.

Little information is available about the effects of lime and mortar other than the observation that the protective film on the surface of aluminum is sensitive to these materials.

Cases of rapid failure of aluminum have been caused by contact with copper, or are the result of wetting with water which has passed over copper or nickel. Contact of aluminum with steel plates and bolts requires special consideration, especially where insulation is impossible.

4.2 Zinc

Zinc is rarely used in pure form. It is often alloyed with copper to give brass or plated on iron to give the galvanized product. Upon initial exposure to the atmosphere zinc forms a thin film of zincite (zinc (II) oxide, ZnO) which rapidly transforms to zinc hydroxide/8,14/.

$$Zn^{\circ} + H_2O \longrightarrow Zn(OH)_2 + 2H^{+} + 2e^{-} \qquad (8)$$

When zinc hydroxide is exposed to CO_2 zinc carbonates are formed. The most abundant carbonate species detected on the surface are smithsonite ($ZnCO_3$) and the hydroxycarbonate mixed salt hydrozincite ($Zn_5(CO_3)_2(OH)_6$). Zinc carbonate is however only stable between pH6 and 7. In near neutral or basic solutions, as is the case in dew or adsorbed water vapour,

zinc hydroxide is expected to predominate. In acidic solutions, eg, rain, fog, the stable form of zinc is the divalent ion/8/.

Zinc dihydroxide is readily dissolved in acidic solutions, it is therefore assumed that the corrosion products that form on zinc form in the surface aqueous layer and not in the solid phase.

The coating formed by zinc upon exposure to the atmosphere is considerably less protective than that formed by aluminum. Many rates of corrosion for zinc in various atmospheres have been reported. Typical rates in rural areas are 0.2-0.3 $\mu m\ year^{-1}$, 2-16 $\mu m\ year^{-1}$ in urban and industrial areas and 0.5-8 $\mu m\ year^{-1}$ at marine sites/8/. The rates of corrosion of zinc do not decrease with time but are dependent upon changes in the local concentrations of corrodents/3/. The corrosion of zinc involves only the Zn^{2+} ion, no oxidation or reduction reactions are possible.

Field work suggests that zinc corrosion is a process of sequential dissolution, concentration, redistribution and precipitation. In an acidic environment, pH 3, there is rapid dissolution of the metal. As the reaction proceeds, the pH will increase until a basic salt precipitates, the carbonate. The carbonate will inhibit corrosion until an additional supply of acid is dissolved. Hence the alternating destruction and buildup of the protective film/1/. The composition of the surface film is therefore not uniform with depth. The outer surface layer, approximately 15 nm, appears to be ZnO while deeper into the film high concentrations of $ZnCO_3$ or $Zn(OH)_2$ are observed. The extreme outer layer, 1 nm, may also be rich in chlorine and sulfur.

Some of the reactions of zinc with atmospheric pollutants are summarized in Figure 2.

Even in the absence of anthropogenic acids such as HNO_3 and H_2SO_4 some dissolution of zinc on galvanized steel is expected since the film of moisture will be acidified as a result of the production of carbonic acid formed by reactions with dissolved CO_2, equation 12. Dissolution of the relatively insoluble $ZnCO_3$ generates CO_3^{2-}, equation 9, which reacts with H^+ ions.

$$ZnCO_3 \rightleftharpoons Zn^{2+} + CO_3^{2-} \qquad (9)$$

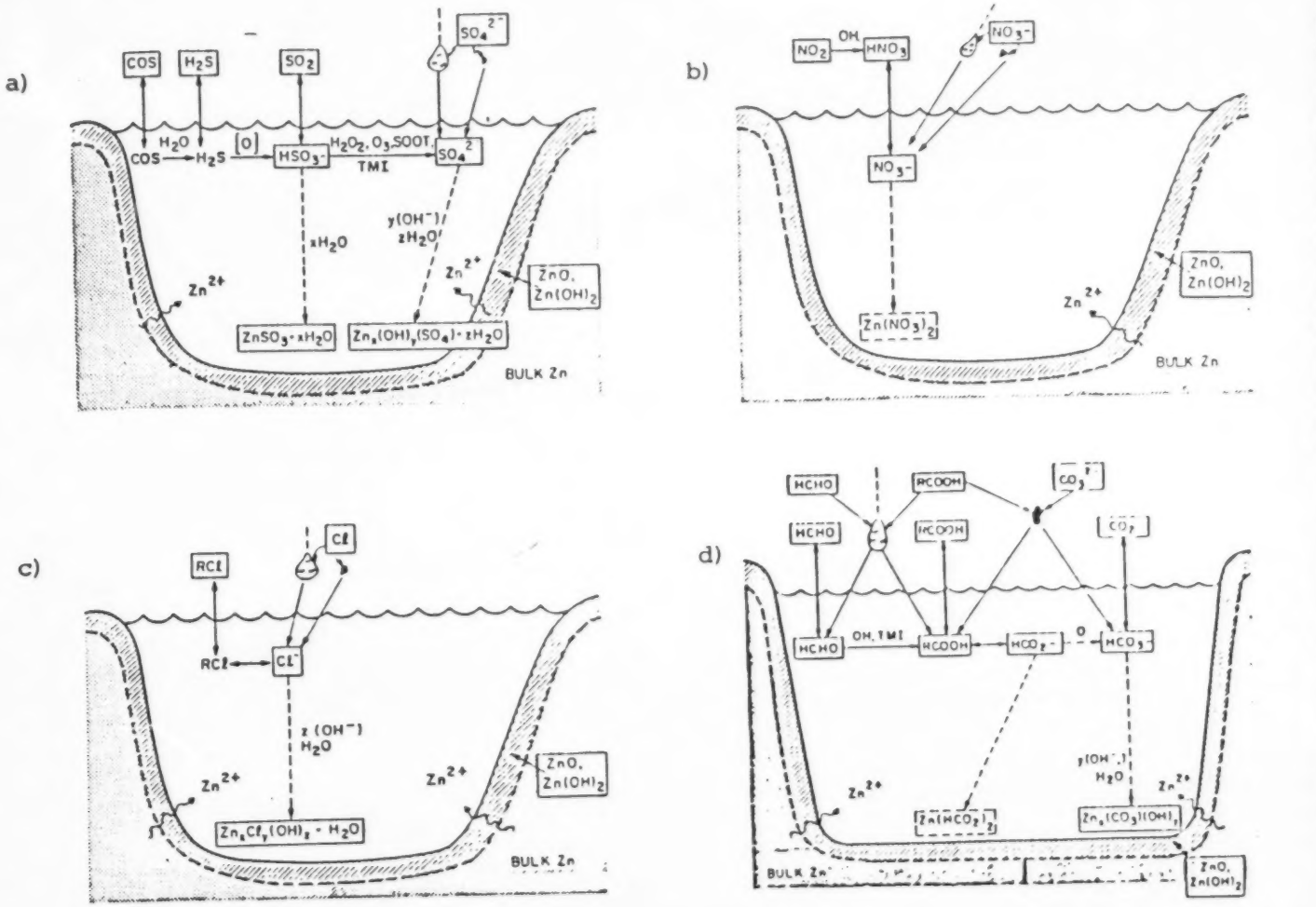
$$H^+ + CO_3^{2-} \rightleftharpoons HCO_3^{2-} \qquad (10)$$

$$HCO_3^{2-} + H^+ \rightleftharpoons H_2CO_3 \qquad (11)$$

$$H_2CO_3 \rightleftharpoons CO_2 + H_2O \qquad (12)$$

Removal of CO_3^{2-} shifts the equilibrium of equation 9 resulting in increased dissolution of $ZnCO_3$. Dry deposition of basic particles such as $CaCO_3$ may offer some protection since they readily react with acids/15/.

Figure 2. A schematic representation of the processes involved in the atmospheric corrosion of zinc. The sulfur chemistry is shown in Figure 2a and similarly the reactions of nitrogen containing species in 2b, chlorine species in 2c and carbonate and organic compounds in 2d. The atmosphere is at the top of the diagrams, a surface water layer is in the centre, and the corroding metal is at the bottom. The diagram pictures a depression in the metal surface, although deposited hygroscopic particles, heavy dew, or rain could produce similar conditions anywhere on the surface. The wavy lines indicate zinc ions diffusing into the aqueous solution from the bulk solid. Species whose presence in the indicated phase has been confirmed by field measurements are enclosed in a rectangular box; the presence of other species has not been confirmed. Reaction processes confirmed by laboratory studies are indicated by solid arrows, those which are uncertain are shown as dotted arrows. Rain is indicated by the atmospheric water drop and airborne particles by the irregular small atmospheric object/8/.



Reactions of SO_2 on zinc surfaces are comparable to those on steel but ZnO, contrary to Fe_3O_4 (magnetite), is not electroconductive. Therefore the corrosion reactions are slower despite the fact that zinc is less noble than iron. A number of reactions describing the formation of zinc sulfate, zinc sulfite, zinc sulfide and hydrated zinc sulfates are given below, equations 13-16/8,13/.

$$SO_2 + O_2 + Zn \longrightarrow ZnSO_4 \qquad (13)$$

$$SO_2 + 2O_2 + 2Zn \longrightarrow 2ZnSO_3 \qquad (14)$$

$$SO_2 + 3Zn \longrightarrow ZnS + 2ZnO \qquad (15)$$

$$Zn^{2+} + SO_4^{-} + xH_2O \longrightarrow ZnSO_4 \cdot xH_2O \quad (x = 4,6,7) \qquad (16)$$

Zinc sulfates are abundant on zinc exposed to the outdoor environment. Two other sulfate containing species, hydroxysulfates, are also common, equation 17.

$$yZn(OH)_2 + ZnSO_4 + 4H_2O \longrightarrow Zn_{y+1}(SO_4)(OH)_{2y} \cdot 4H_2O \quad (y = 3,6) \qquad (17)$$

The stability of zinc hydroxysulfates is however uncertain/8/.

An insoluble zinc patina may react with SO_2 to give zinc sulfate which may be washed away by rain water, equation 18/5/.

$$2Zn(HCO_3)_2 + 2SO_2 + O_2 \longrightarrow 2ZnSO_4 + 4CO_2 + 2H_2O \qquad (18)$$

The amount of corrosion produced on zinc is approximately equivalent to the amount of SO_2 taken up. In work reported by Carter et al/16/, the corrosion film on galvanized steel saturates with sulfur at atmospheric sulfur dioxide concentrations of approximately 30 ppb. The saturation limit is approximately 7 wt % sulfur and is related to the formation of a series of basic zinc sulfate salts, which together with the basic zinc carbonate, compose the bulk of the corrosion film.

In the case of chlorine, some zinc chlorides have been identified. The salts $Zn_5(OH)_8Cl_2$ and $4ZnO \cdot ZnCl_2 \cdot H_2O$ have been observed on samples exposed to industrial and marine atmospheres. The fact that the chlorine compounds are not very abundant may be due to the tendency of the simple zinc chloride salts to be washed away rather than incorporated into more complex minerals.

H_2O_2 is believed to enhance zinc corrosion.

When zinc is exposed to relatively high concentrations of gaseous formaldehyde or formic acid in the laboratory, surface formates are generated. Formaldehyde and formic acid are common constituents of atmospheric precipitation; it is therefore expected that they might have some impact on the atmospheric corrosion of zinc. Laboratory studies suggest that the dry deposition of HCHO into dew enhances the dissolution of zinc. Although $HCOO^-$ is believed

to be produced in dew it has not been detected in dew, it has however been detected in the runoff water. The poor stability of formate may be the cause of the difficulty in detecting it/14/.

Zinc is also sensitive to alkaline materials and should not be exposed to cement or lime mortar/1/. Identification of the interaction between zinc and alkali salts requires additional work.

4.3 Corrosion of Transmission Line Conductors

The previous sections have described some of the corrosion reactions of aluminum and zinc. However as discussed initially the corrosion of transmission line conductors is not as simple as the corrosion of two pure, well separated metals. In the case of conductors, two and sometimes three metals (aluminum, zinc and iron) are in direct contact. This interaction can result in galvanic corrosion. The crevices formed by the winding of the wires may also be starting points for corrosion. This section will address these aspects of corrosion.

4.31 Galvanic Corrosion

Intense corrosion, greater than that observed when only one metal is present can occur where a base (reactive) metal is in contact with a more noble (unreactive) metal. This results in accelerated corrosion of the base metal and a reduction or prevention of attack on the noble metal. To illustrate, when iron is in contact with zinc, the zinc corrodes; when iron is in contact with aluminum, the aluminum corrodes. Laboratory studies suggest that aluminum coupled to steel is attacked three times as fast as aluminum coupled to aluminum/10/. In the case of zinc and aluminum, zinc protects aluminum. The presence of carbon, graphite or coke can stimulate corrosion on most metals.

4.32 Crevice Corrosion

In a crevice there is little replenishment of the oxygen required for some metals to rebuild their protective oxide coating, therefore intense corrosion may occur. Hydrolysis of the salt formed by the anodic reaction in a crevice, which contains only a small amount of liquid, can result in big changes in the pH of the solution. This increased acidity of the liquid in the crevice relative to that outside may further stimulate attack.

Gaseous and solid pollution can penetrate into the conductors via the crevices formed by the winding of the wires. When the conductor has been thoroughly wetted by rain, the interstices between the strands will retain the moisture by capillary forces and the conditions will be similar to that of complete immersion.

4.33 Transmission Line Conductor Corrosion

In 1954 Forest and Ward/17/ published a paper on the condition of transmission line conductors in Great Britain. They reported that the outer layer of the aluminum wires of the conductors exposed to industrial areas were coated with a black scale having an outer friable layer. The composition of the black layer varied from area to area, but was found to contain some carbon, heavy metal dusts and a percentage of soluble material. The carbon was believed to assist the corrosion process by adsorbing sulfur oxides and concentrating them at the surface of the metal. Carbon could also act as an oxygen electrode and in the presence of moisture which would serve as an electrolyte, a corrosion cell could be formed with carbon as the cathode and aluminum as the anode. When the black layer was removed, a thinner, more tenacious scale flecked with grey patches was left. Between the aluminum strands and between the aluminum and steel core wires they observed a grey-white corrosion product. Deep elongated pits were observed under the corrosion product and distributed uniformly over the strands. Some of the zinc was removed from the galvanized steel core but the steel was not heavily attacked.

In coastal regions serious corrosion resulting in the formation of bulges or swellings between the steel core and aluminum strands was observed. Tests in the laboratory using sea water (synthesized) suggest that the potentials of the metals zinc, aluminum and steel increase in going from zinc to steel. Therefore in the initially formed corrosion cell zinc is the anode and aluminum is the cathode and zinc corrodes. When sufficient galvanizing has been removed, a new corrosion cell is set up with aluminum as the anode and steel as the cathode. Therefore the aluminum corrodes and the steel remains unattacked. The corrosion product, aluminum oxides, is deposited between the strands. The amount of product gradually builds up, acting as an absorbent to retain electrolyte and to force the strands apart to permit further ingress of electrolyte. The voluminous nature of the corrosion product may tend to lever the plates apart/10/.

Accelerated linear corrosion of aluminum in galvanic contact with carbon or steel has been observed on CEGB electricity transmission lines, with localized pitting due to carbon particles, and galvanic corrosion under graphite loaded rubber bushes/6/.

5.0 CONCLUSIONS

This paper has reviewed the corrosion of aluminum and zinc by a number of atmospheric pollutants. Atmospheric corrosion is very dependent upon the presence of moisture. The pollutants of primary concern and those about which the most information is available are sulfur dioxide, the sulfate and chloride ions and salts. The study of the corrosion of transmission line conductors is complicated by the direct contact of the aluminum and galvanized steel wires and the crevices formed as a result of the winding of the aluminum wires around the galvanized steel core. More information is needed about the effects of alkali salts, such as calcium hydroxide, on the atmospheric corrosion of these materials.

The information presented in this review suggests that at least initially, when trying to estimate the life of transmission line conductors, one must consider the local concentrations of pollutants such as sulfur dioxide, sulfate and chloride salts, the pH of precipitation and

meteorological factors such as relative humidity and amount of precipitation. Pollutant and meteorological data are available for selected sites in the province from the Ontario Ministry of the Environment and the Atmospheric Environment Service. This data may be used to identify regions of the province where air pollutants may cause significant rates of transmission line conductor corrosion. Subsequent papers will examine the relationship between this data and the condition of Ontario Hydro's transmission system.

Approved by:

D.J.R. Dodd
Manager
Chemical Research Department

Prepared by:

A. Kalvins
Scientist - Environmental Controls
Environmental Science Section

Reviewed by:

O.T. Melo
Supervising Engineer
Environmental Science Section

REFERENCES

1. Atmospheric Corrosion, W.H. Ailor editor, Wiley Interscience 1982 and references therein.

2. F.W. Lipfert, Materials Performance, July 1987.

3. Atmospheric Chemical Compounds, Sources, Occurrence and Bioassay, T.E. Graedel, D. T. Hawkins, L.D. Claxton, Academic Press, 1986.

4. J.R. Walton, J.B. Johnston and G.C. Wood (1982) Br. Corros. J. 17 (2) 65.

5. F.W. Lipfert (1989) JAPCA 39 446-452.

6. Air Pollution, Acid Rain and the Environment, Watt Committee Report, Number 18, Kenneth Mellanby editor, Elsevier Applied Science Publishers, London 1988.

7. U.R. Evans (1968) The Corrosion and Oxidation of Metals: First Supplementary Volume. Edward Arnold (Publishers) Ltd. London.

8. T.E. Graedel (1989) J. Electrochem. Soc. 136 (4) 193C, and references therein.

9. Degradation of Metals in the Atmosphere, ASTM STP965 (1987) and references therein.

10. U.R. Evans (1960) The Corrosion and Oxidation of Metals: Scientific Principles and Practical Applications. Edward Arnold (Publishers) Ltd. London.

11. Materials Degradation Caused by Acid Rain, R. Baboian, editor, ACS Symposium Series 318, American Chemical Society, 1986 and references therein.

12. T.E. Graedel (1989) J. Electrochem. Soc. 136 (4) 204C, and references therein.

13. U.R. Evans (1976) The Corrosion and Oxidation of Metals: Second Supplementary Volume. Edward Arnold (Publishers) Ltd. London.

14. E.O. Edney, D.C. Stiles, E.W. Corse, M.L. Wheeler, J.W. Spence, F.H. Haynie, W.E. Wilson Jr. (1988) Materials Performance, 47.

15. E.O. Edney, S.F. Cheek, D.C. Stiles, E.W. Corse, M.L. Wheeler, J.W. Spence, F.H. Haynie, W.E. Wilson (1988) Atmos. Environment 22 (10) 2263.

16. J.P. Carter, P.J. Lindstrom, D.R. Flinn and S.D. Cramer (1987) Material Performance (July).

17. J.S. Forest, J.M. Ward (1954) J. Instn. elect. Eng. 101, part II, 271.